DORA MEMO #001
ASU LOCO MEMO #046

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Sources of background light for DORA cubesat and ground station

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1. Overview

Background light sources will contribute to the power received by a DORA-style receiver on the ground or in LEO. The large field of view (about π steradians) of the DORA receiver makes it more susceptible to background light than narrow field systems for two reasons: 1) bright sources are more likely to be in the field of view and 2) diffuse background emission will integrate to larger power than for narrow field of view systems. Additionally, the baseline design for DORA uses photodiode detectors that have broadband response (~500nm) unless special filters or coatings are applied. Hence, thermal and other broadband background light sources can integrate to large power in these detectors.

I find that for either Silicon or InGaAs-based detector systems, atmospheric line emission (e.g. OH lines), also called airglow, and light pollution may be a significant or even dominate contribution to the received power of a DORA system on the ground or in LEO. I also find that if a laser wavelength of 1550nm is chosen and InGaAs photodiodes are used as detectors, the Earth's thermal radiation may create a background as large as ~1% of the expected link power. Diffuse astronomical sources, such as Zodiacal light and faint stars, are generally not dominate sources of background light. Table 1 summarizes the expected background power levels received by DORA.

Mitigation strategies include using narrow passband filters or coatings on the DORA receiver, which could reduce the broadband backgrounds by ~20 dB. In addition, using a more traditional small field of view telescopic receiver system on the ground would further reduce its susceptibility to broadband emission from the atmosphere and sky by ~40 dB for a telescope with 1 degree field of view.

Further modeling of the main background contributions is needed to include the actual emissivity of the Earth in the surface area visible to DORA, atmospheric absorption (there are a couple strong absorption lines between 800 and 1500nm), and detailed detector sensitivity as a function of wavelength. Additional investigation of the Zodiacal light background and its variations with position is also warranted.

While adopting a 1550nm laser would raise the TRL of a system most relevant to future deep space DORA instruments, the large OH line emission from the Earth's atmosphere makes that wavelength more challenging for a system operating in LEO.

Source	**Total band power**		**10nm passband power**	
	Silicon (400-950 nm)	**InGaAs (1000-1600 nm)**	**850nm**	**1550nm**
Link on orbit	-30	-30	-30	-30
Link on ground	-36	-36	-36	-36
Earth BB	-141	-59	-167	-70
Sun BB	+39	+34	+20	+13
Sunlight reflected from Earth	+30	+25	+11	+5
Moonlight reflected from Earth	-29	-34	-48	-54
Atmosphere molecular lines	-43	-32	-62	-50
Atmosphere light pollution	?	?	?	?
Zodiacal light	-56	-61	-74	-81
Faint stars	-56	-61	-74	-81

Table 1. Summary of expected power levels received by DORA. All values in dBm.

2. Detector wavelength bands and the DORA instrument

The DORA system is currently evaluating two wavelengths for its infrared link laser. These are λ=850nm and λ=1550nm. The 850nm system would likely use Silicon photodiodes as detectors. The 1550nm system would likely use InGaAs photodiodes as detectors. Each of these detectors has a broadband response curve that spans ~500nm, but the bands are centered at different wavelengths, as summarized in Table 2 and Figure 1. Narrow passband filters or coatings could be installed on the DORA detectors to limit their response away from the link laser wavelength. The narrowest usable bandpass, given that the velocity of DORA in orbit is about 0.01% the speed of light, would be about 0.2nm. In practice, it seems filters are generally available with 1-100nm passbands and I take a 10nm passband as a reference.

Laser wavelength [nm]	**Detector/filter technology**	**Response band [nm]**
850	Silicon photodiode Nominal full band	400-950
850	Silicon photodiode Filtered 10nm passband	845-855
1550	InGaAs photodiode Nominal full band	1000-1600
1550	InGaAs photodiode Filtered 10nm passband	1545-1555

Table 2 – Wavelengths bands for nominal detectors and filters under consideration for DORA

I use the following other reference design properties for DORA:

Parameter	Value	Unit
Ground station transmitter power	1	W
On orbit transmitter power	0.25	W
Transmitter beam opening angle	0.0143	degrees
Receiver aperture area	0.01	m^2

Table 3 – DORA transmitter and receiver properties

3. Received power calculations

3.1. Link power

I begin by calculating the expected power that DORA terminal in orbit will receive from the ground station transmitter and vice versa. This is essentially independent of the wavelength chosen for the laser (assuming ideal detectors). The relevant instrument design parameters are given in Table 3. The ground station will use a 1 W laser. The goal is to have a 100 meter diameter spot size at the distance of the DORA orbit (nominally 400 km). Thus, the beam opening angle of the ground station laser will be ~0.0143 deg. The maximum flux of the ground station laser at the orbital altitude of DORA will be:

$$F_{orbit} \approx 1\ W / (100m)^2 \approx 10^{-4}\ W/m^2.$$

Using the nominal aperture area for the DORA receiver of 0.01 m^2, the ground transmitter will be received in orbit with power:

$$P_{orbit} = 10^{-6}\ W = -30\ dBm$$

The DORA terminal on the cubesat will use a 0.25 W laser and will have a similar beam opening angle of ~0.0143 deg. The flux of received at the ground station will be:

$$F_{surface} \approx 0.25\ W / (100m)^2 \approx 2.5 \times 10^{-5}\ W/m^2.$$

and using the same nominal ground station receiving aperture, the received power on the ground from DORA will be:

$$P_{surface} = 2.5 \times 10^{-7}\ W = -36\ dBm$$

3.2. Thermal blackbody sources

The Earth and Sun are the two primary thermal background sources. Both can be approximated reasonably as a thermal blackbody with 100% emissivity. For the Earth, I assume a temperature of T_{earth}=300 K and that the Earth fills an entire half-sky from DORA's vantage in LEO. Applying the cos(θ) dependence of DORA's detectors and the nominal aperture area of the DORA receiver, the result is Earth contributes a total received power of (see Appendix A and B for details):

Silicon band: $P_{earth} \approx 10^{-17}$ W = -140 dBm
InGaAs band: $P_{earth} \approx 10^{-9}$ W = -60 dBm

The integrated thermal power from the Earth in the Silicon full band is nearly 100 dB below the expected link power received from the transmitter. However, it is only about 25 dB below the expected link power in the InGaAs full band.

For the Sun, assuming a temperature T_{sun}=5778 K, the total flux and power received by the DORA receiver in orbit over each of the photodiode bands will be:

Silicon band: $P_{sun} \approx 8$ W = +39 dBm
InGaAs band: $P_{sun} \approx 2.5$ W = +34 dBm

It is easy to see that if the Sun is visible to the DORA receiver, its power will be at least 60 dB above the expected link power. For DORA in LEO, I can limit operations to nighttime to avoid the sun. However, for a DORA in deep space, other mitigation would be needed, such as reducing the overall field of view to avoid the sun.

3.3. Atmospheric emission (airglow) and light pollution

Atmospheric emission below ~900nm is due primarily to weak molecular lines in the upper atmosphere and ionosphere. Above ~900nm stronger OH lines in the ionosphere at an altitude of about 90 km are a significant source of power. Leinert et al. 1997 (see Figures 2-4 below) provides reference surface brightness values for atmospheric emission lines/airglow:

Si band (O_2 + light pollution): ~ 1 W / m^2 / str / m
InGaAs band (OH lines): ~ 10^1 W / m^2 / str / m

Using the bandpass ranges for each of the detector types, and assuming again that the atmosphere fills an entire half-sky from the perspective of the cubesat or ground station, I find that atmospheric emission fluxes and received powers are:

Silicon band: $P_{airglow} \approx 3.5 \times 10^{-8}$ W = -45 dBm
InGaAs band: $P_{airglow} \approx 5.7 \times 10^{-7}$ W = -32 dBm

Atmospheric line emission will be a significant contribution to the received power in both bands. Light pollution will add to these levels especially in a metropolitan environment like around Tempe, Az.

3.4. Additional astronomical background sources (mostly relevant for the ground station)

In general, other diffuse astronomical contributions to the background light will be below the atmosphere emission, as shown in Figure 4. For example, Zodiacal light is among the strongest astronomical contributions to the visible and near-IR bands (this is reflected sunlight, thermal dust emission is at longer wavelengths). It would contribute about 10^{-7} W/m^2/str in the DORA bands (Leinert et al. 1997). Integrating over the DORA field to get the flux and then multiplying by the DORA collecting area to calculate power yields:

Silicon and InGaAs bands: $P_{zodiacal} \approx 10^{-9}$ W/m^2 = -60 dBm

3.5. Moonlight reflected from Earth

The reflection of sunlight off the Moon and then in turn off the Earth will be a common occurrence at night (except during New Moon periods). I calculate this background source starting with the solar blackbody spectrum, estimating the flux at the moon, and then reradiating that flux as its own source and calculating the flux is yields at the Earth, which is then assumed to be perfectly reflected as a new blackbody source. I ignore any reductions to albedo and probably don't have all of the factors of 2 and π quite right. The numbers in Table 1 should be double checked. But if they are correct, then reflected moonlight is only about 15-20 dB below the link power for the full band detectors.

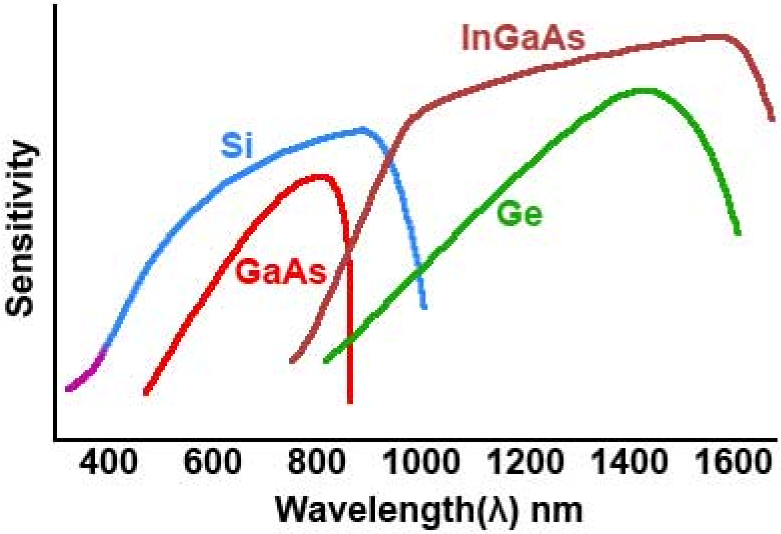

Figure 1. Example passbands of Silicon and InGaAs detectors. Note that sensitivity is the number of electrons generated per Watt of received power (usually expressed in A/W). It is not proportional to quantum efficiency since there are fewer photons per Watt at lower wavelengths. From: https://learnabout-electronics.org/Semiconductors/diodes_27.php

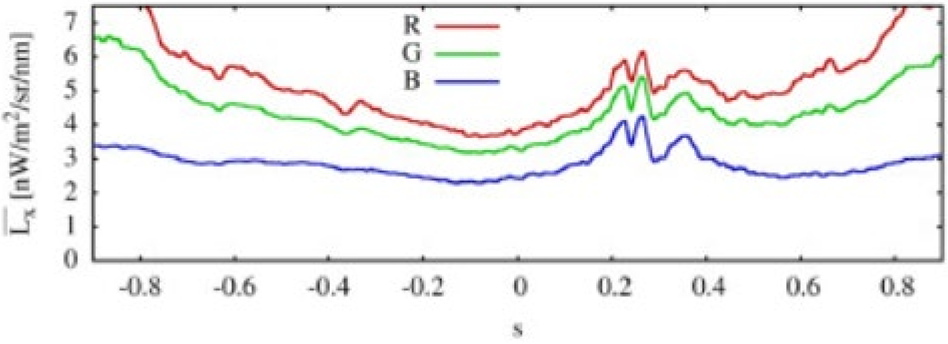

Figure 2. Airglow (and light pollution) measurements in visible color bands. The level in the blue band is taken as the zero reference. From: https://www.sciencedirect.com/science/article/pii/S0022407319309653

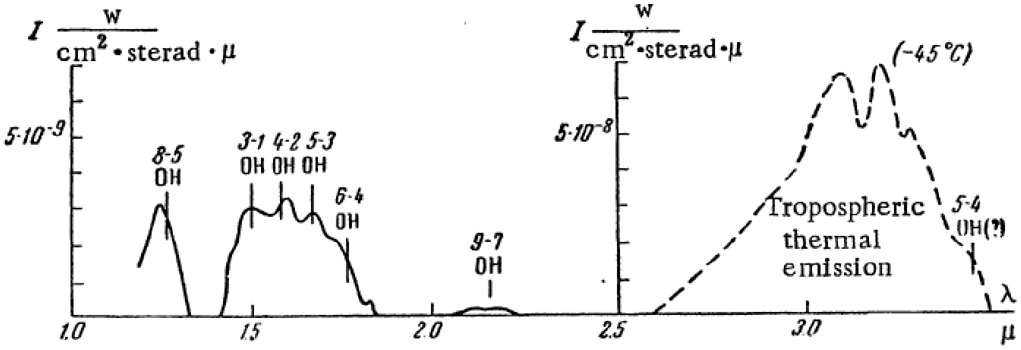

Figure 3. Airglow measurements in the near-IR (including the InGaAs band) from: https://ui.adsabs.harvard.edu/abs/1960SvA.....4..118M

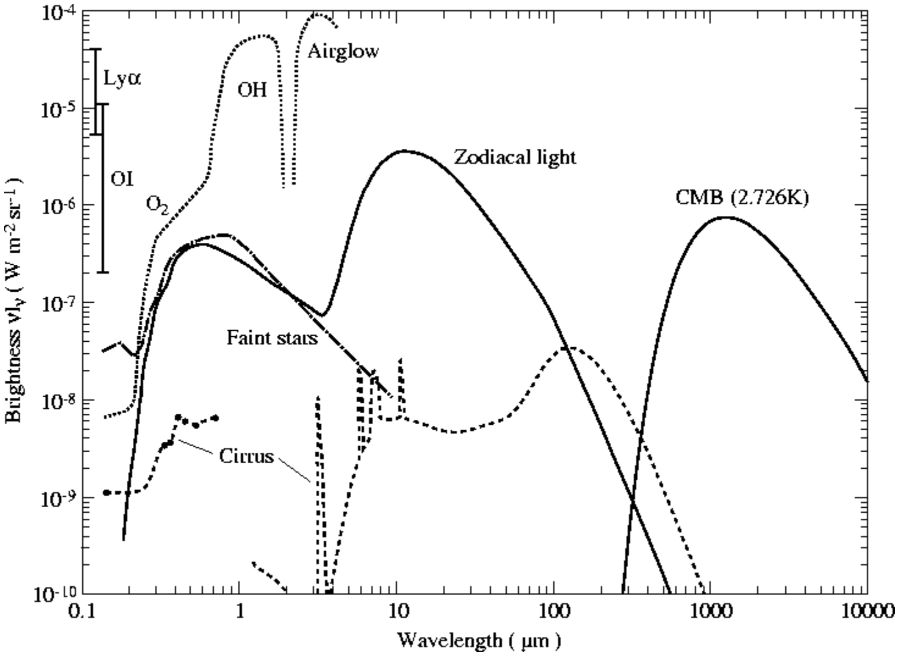

Figure 4. Summary of emission that shows OH atmospheric emission dominates other sources of astronomical contributions. From:
https://aas.aanda.org/articles/aas/full/1998/01/ds1449/node1.html
https://ui.adsabs.harvard.edu/abs/1998A%26AS..127....1L/abstract
For more on Zodiacal light, see also:
https://www.researchgate.net/publication/225614827_Observational_Studies_of_Interplanetary_Dust

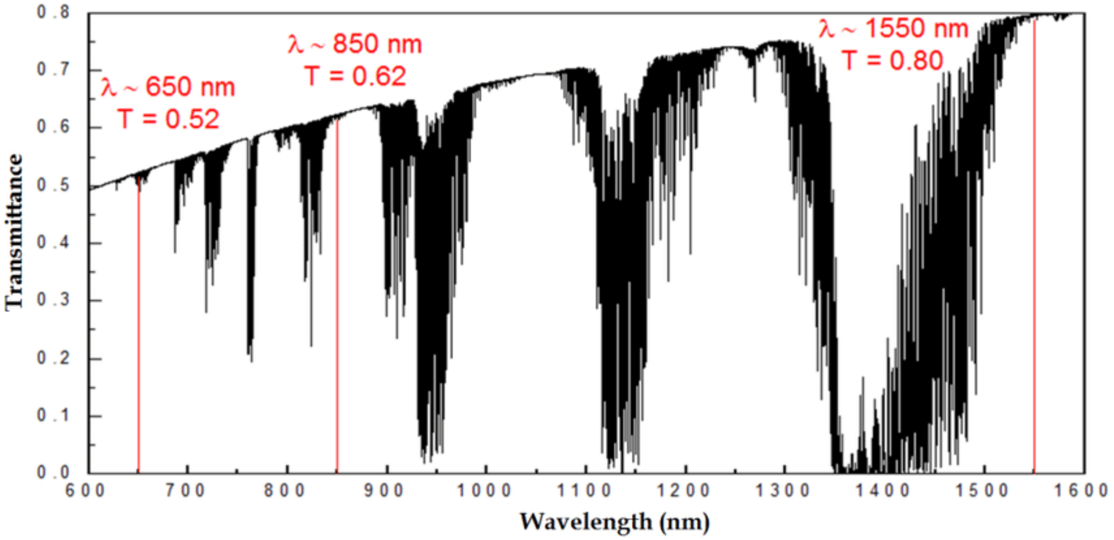

Figure 5. For reference, here is the atmospheric transmission spectrum. A perfect atmosphere transmittance was assumed for the calculations here, but in practice there is considerable absorption. From: https://www.researchgate.net/publication/309731586_Free-Space_Quantum_Key_Distribution

Appendix A: Raw output of calculations

```
--------------------------------------------------------------------
*** BAND: Si (400-950nm) ***
--------------------------------------------------------------------

++ Link flux at orbit:     0.0001 W/m^2
++ Link flux at ground:    2.5e-05 W/m^2

Flux from Earth:           1.121e-15 W/m^2
Flux from Sun:             777.5 W/m^2
Flux from Moon:            0.01588 W/m^2
Flux from Moon glow:       4.361e-06 W/m^2
Flux from O2 lines:        3.456e-06 W/m^2
Flux from OH lines:        0.0001037 W/m^2
Flux from Zodi.:           6.912e-07 W/m^2
Flux from stars:           6.912e-07 W/m^2
Flux from Zodi. #2:        5.442e-07 W/m^2
Flux from stars #2:        5.442e-07 W/m^2

++ Link power at orbit:    1e-06 W      = -30 dBm
++ Link power at ground:2.5e-07 W       = -36.02 dBm

Power from Earth:          7.472e-18 W  = -141.3 dBm
Power from Sun:            7.775 W      = 38.91 dBm
Power from Moon:           0.0001588 W  = -7.993 dBm
Power from Moon glow:      2.18e-08 W   = -46.61 dBm
Power from O2 lines:       3.456e-08 W  = -44.61 dBm
Power from OH lines:       5.184e-07 W  = -32.85 dBm
Power from Zodi.:          3.456e-09 W  = -54.61 dBm
Power from stars:          3.456e-09 W  = -54.61 dBm
Power from Zodi.#2:        2.721e-09 W  = -55.65 dBm
Power from stars #2:       2.721e-09 W  = -55.65 dBm


--------------------------------------------------------------------
*** BAND: InGaAs (1000-1600nm) ***
--------------------------------------------------------------------

++ Link flux at orbit:     0.0001 W/m^2
++ Link flux at ground:    2.5e-05 W/m^2

Flux from Earth:           2.007e-07 W/m^2
Flux from Sun:             244.7 W/m^2
Flux from Moon:            0.004997 W/m^2
Flux from Moon glow:       1.373e-06 W/m^2
Flux from O2 lines:        3.77e-06 W/m^2
Flux from OH lines:        0.0001131 W/m^2
Flux from Zodi.:           7.54e-07 W/m^2
Flux from stars:           7.54e-07 W/m^2
Flux from Zodi. #2:        1.713e-07 W/m^2
Flux from stars #2:        1.713e-07 W/m^2

++ Link power at orbit:    1e-06 W      = -30 dBm
++ Link power at ground:2.5e-07 W       = -36.02 dBm

Power from Earth:          1.338e-09 W  = -58.74 dBm
Power from Sun:            2.447 W      = 33.89 dBm
Power from Moon:           4.997e-05 W  = -13.01 dBm
```

```
Power from Moon glow:      6.864e-09 W  = -51.63 dBm
Power from O2 lines:       3.77e-08 W   = -44.24 dBm
Power from OH lines:       5.655e-07 W  = -32.48 dBm
Power from Zodi.:          3.77e-09 W   = -54.24 dBm
Power from stars:          3.77e-09 W   = -54.24 dBm
Power from Zodi.#2:        8.566e-10 W  = -60.67 dBm
Power from stars #2:       8.566e-10 W  = -60.67 dBm


---------------------------------------------------------------------
*** BAND: 10nm filter centered on 850nm ***
---------------------------------------------------------------------

++ Link flux at orbit:     0.0001 W/m^2
++ Link flux at ground:    2.5e-05 W/m^2

Flux from Earth:           2.601e-18 W/m^2
Flux from Sun:             10.32 W/m^2
Flux from Moon:            0.0002108 W/m^2
Flux from Moon glow:       5.79e-08 W/m^2
Flux from O2 lines:        6.283e-08 W/m^2
Flux from OH lines:        1.885e-06 W/m^2
Flux from Zodi.:           1.257e-08 W/m^2
Flux from stars:           1.257e-08 W/m^2
Flux from Zodi. #2:        7.226e-09 W/m^2
Flux from stars #2:        7.226e-09 W/m^2

++ Link power at orbit:    1e-06 W      = -30 dBm
++ Link power at ground:2.5e-07 W       = -36.02 dBm

Power from Earth:          1.734e-20 W  = -167.6 dBm
Power from Sun:            0.1032 W     = 20.14 dBm
Power from Moon:           2.108e-06 W  = -26.76 dBm
Power from Moon glow:      2.895e-10 W  = -65.38 dBm
Power from O2 lines:       6.283e-10 W  = -62.02 dBm
Power from OH lines:       9.425e-09 W  = -50.26 dBm
Power from Zodi.:          6.283e-11 W  = -72.02 dBm
Power from stars:          6.283e-11 W  = -72.02 dBm
Power from Zodi.#2:        3.613e-11 W  = -74.42 dBm
Power from stars #2:       3.613e-11 W  = -74.42 dBm


---------------------------------------------------------------------
*** BAND: 10nm filter centered on 1550nm ***
---------------------------------------------------------------------

++ Link flux at orbit:     0.0001 W/m^2
++ Link flux at ground:    2.5e-05 W/m^2

Flux from Earth:           1.541e-08 W/m^2
Flux from Sun:             2.272 W/m^2
Flux from Moon:            4.638e-05 W/m^2
Flux from Moon glow:       1.274e-08 W/m^2
Flux from O2 lines:        6.283e-08 W/m^2
Flux from OH lines:        1.885e-06 W/m^2
Flux from Zodi.:           1.257e-08 W/m^2
Flux from stars:           1.257e-08 W/m^2
Flux from Zodi. #2:        1.59e-09 W/m^2
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```
Flux from stars #2:        1.59e-09 W/m^2

++ Link power at orbit:    1e-06 W       = -30 dBm
++ Link power at ground:2.5e-07 W        = -36.02 dBm

Power from Earth:          1.027e-10 W  = -69.88 dBm
Power from Sun:            0.02272 W           = 13.56 dBm
Power from Moon:           4.638e-07 W  = -33.34 dBm
Power from Moon glow:      6.37e-11 W   = -71.96 dBm
Power from O2 lines:       6.283e-10 W  = -62.02 dBm
Power from OH lines:       9.425e-09 W  = -50.26 dBm
Power from Zodi.:          6.283e-11 W  = -72.02 dBm
Power from stars:          6.283e-11 W  = -72.02 dBm
Power from Zodi.#2:        7.95e-12 W   = -81 dBm
Power from stars #2:       7.95e-12 W   = -81 dBm
```

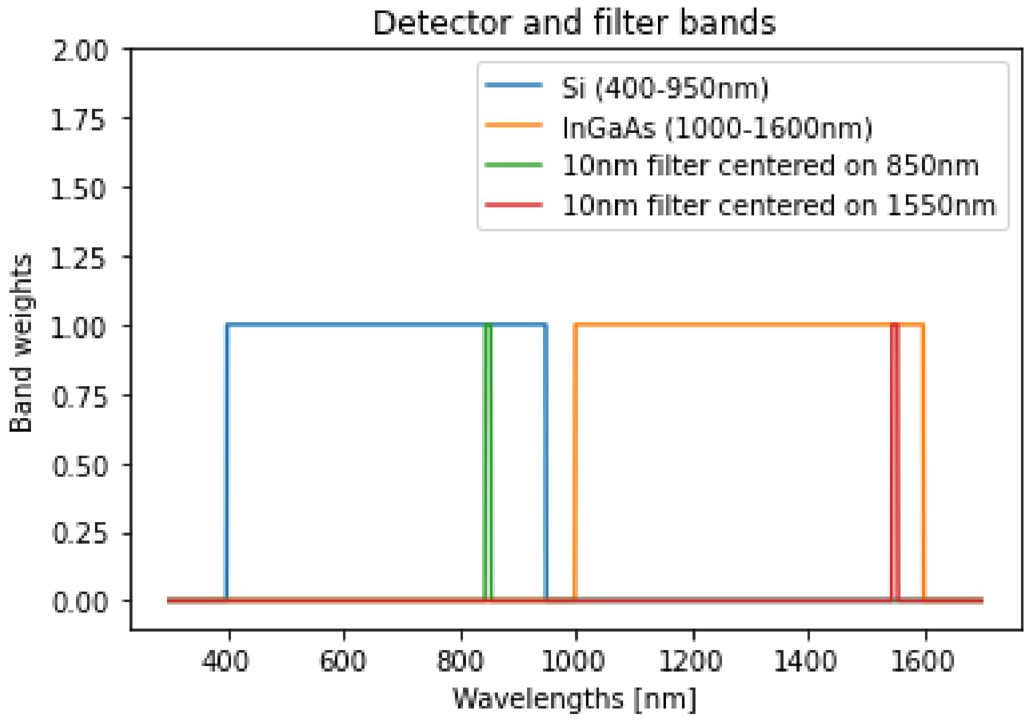

Figure 6 – Bandpass shapes used in the calculations

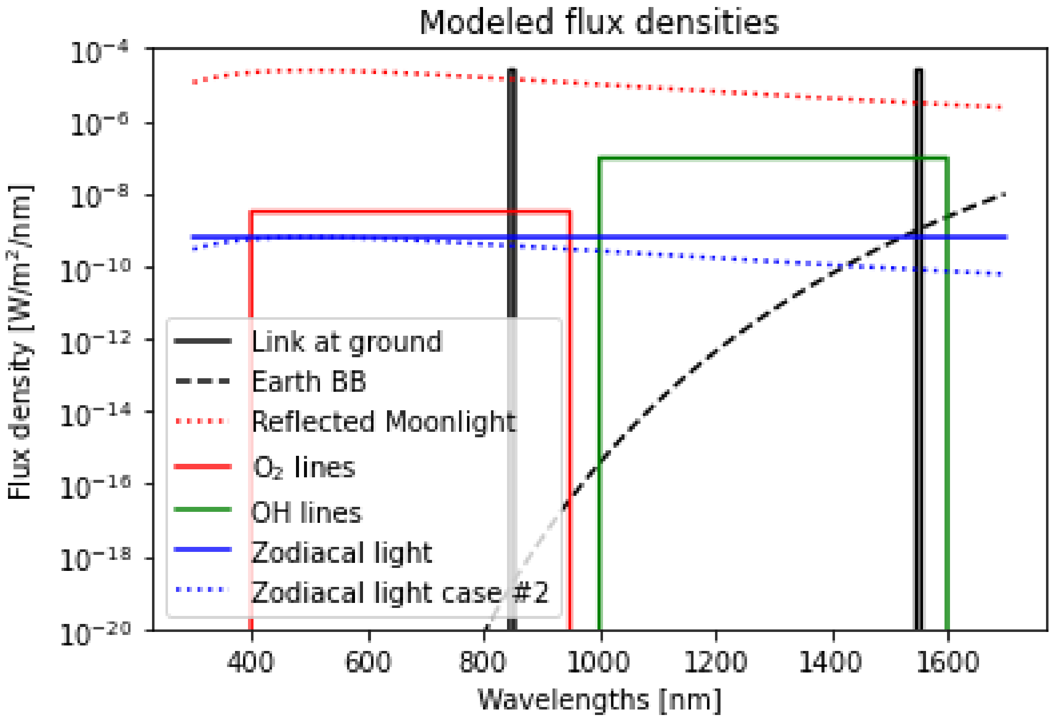

Figure 7 – Flux densities for the modeled sources.

Appendix B: Python script

```
import numpy as np
import scipy.integrate as integrate
import matplotlib.pyplot as plt

# Returns the blackbody specific intensity spectrum  in SI units as a function
# of wavelength.  The function takes two arguments as input:
#  1. an array wavelengths at which to provide the spectrum points
#  2. the temperature of the blackbody
def blackbody_lambda(lmb, temperature):

  h = 6.62607004e-34; # m^2 / kg / s
  c = 2.99792458e8; # m / s
  k = 1.38064852e-23; # m^2 kg / s^2 / K

  B = (2 * h * c**2 / lmb**5) / (np.exp(h * c / (lmb * k * temperature)) - 1);

  return B;

# Returns the blackbody specific intensity spectrum  in SI units as a function
# of frequency.  The function takes two arguments as input:
#  1. an array frequencies at which to provide the spectrum points
#  2. the temperature of the blackbody
def blackbody_nu(nu, temperature):

  h = 6.62607004e-34; # m^2 / kg / s
  c = 2.99792458e8; # m / s
  k = 1.38064852e-23; # m^2 kg / s^2 / K

  B = (2 * h * nu**3 / c**2) / (np.exp(h * nu / (k * temperature)) - 1);

  return B;


# ----------------------------------------------------------------------------
# Define instrument properties
# ----------------------------------------------------------------------------

# Wavelengths
dn = 1e-9 # nm
lambdas = dn * np.arange(300, 1700) # array of integer wavelengths in nm

# Pandbass for detectors and filters
band_name = ['Si (400-950nm)',
             'InGaAs (1000-1600nm)',
             '10nm filter centered on 850nm',
             '10nm filter centered on 1550nm']

band = np.array([
  np.where((lambdas >= 400*dn) & (lambdas < 950*dn), 1, 0),   # si
  np.where((lambdas >= 1000*dn) & (lambdas < 1600*dn), 1, 0), # ingaas
  np.where(np.abs(lambdas-850*dn) < 5*dn, 1, 0),       # 10nm filter on 850nm
  np.where(np.abs(lambdas-1550*dn) < 5*dn, 1, 0) ])    # 10nm filter on 1550nm

# Receiver collecting area
A_gnd = 0.01 # m^2
A_orb = 0.01 # m^2

# Receiver field of view
Omega_1deg = (1 * (np.pi/180))**2;
Omega_dora = np.pi;
```

```
# Transmitter power
P_trans_gnd = 1 # W
P_trans_orb = 0.25 # W

# Transmitter beam opening angle
beam_angle_gnd = 0.00025 # radian
beam_angle_orb = 0.00025 # radian

# Orbit altitude
R_orbit = 400e3 # m



# ----------------------------------------------------------------------------
# Define source properties
# ----------------------------------------------------------------------------

# Earth and Sun
T_earth = 300 # K
R_earth = 6371e3 # m

T_sun = 5778 # K
R_sun = 6.96340e8 # m
d_sun = 1.496e11 # m

R_moon = 1737e3 # m
d_moon = 384400e3 # m

B_earth = blackbody_lambda(lambdas, T_earth)  # W/m^2/str/m
B_sun = blackbody_lambda(lambdas, T_sun) # W/m^2/str/m
B_moon = (R_sun/d_sun)**2 * B_sun # W/m^2/str/m
B_moonglow = (R_moon/d_moon)**2 * B_moon # W/m^2/str/m -- Sun light reflected off the
moon and then reflected off the earth

# Non-thermal source sufrace brightnesses (from Leinert et al. 1997)
B_o2 = 1 # W/m^2/str/m
B_oh = 3e1 # W/m^2/str/m
B_zodiac = 0.2 # W/m^2/str/m
B_stars = 0.2 # W/m^2/str/m

B_zodiac2 = B_sun * 0.2/np.max(B_sun)
B_stars2 = B_sun * 0.2/np.max(B_sun)


# ----------------------------------------------------------------------------
# Calculate Fluxes
# ----------------------------------------------------------------------------
cos_factor = 1/2; # integral of cos(theta) sin(theta) dtheta from 0 to pi/2
cos2_factor = 1/3; # integral of cos(theta)^2 sin(theta) dtheta from 0 to pi/2

F_earth = []
F_sun = []
F_moon = []
F_moonglow = []
F_o2 = []
F_oh = []
F_zodiac = []
F_stars = []
F_zodiac2 = []
F_stars2 = []

P_earth = []
```

```
P_sun = []
P_moon = []
P_moonglow = []
P_o2 = []
P_oh = []
P_zodiac = []
P_stars = []
P_zodiac2 = []
P_stars2 = []

F_link_gnd = []
F_link_orb = []
P_link_gnd = []
P_link_orb = []

for b, name in zip(band, band_name):

  # Background fluxes
  F_earth.append(   np.sum(cos_factor * 2*np.pi * b * B_earth)*dn )
# cos from blackbody lambertian term
  F_sun.append(     np.sum((R_sun/d_sun)**2 * cos_factor * 2*np.pi * b * B_sun)*dn )
# cos from blackbody lambertian term
  F_moon.append(    np.sum((R_moon/d_moon)**2 * cos_factor * 2*np.pi * b * B_moon)*dn
)  # cos from blackbody lambertian term
  F_moonglow.append(np.sum((R_earth/d_moon)**2 * cos_factor * 2*np.pi * b *
B_moonglow)*dn )  # cos from blackbody lambertian term
  F_o2.append(      np.sum(2*np.pi * b * B_o2)*dn )
# Does this need cos factor like BB radiation?
  F_oh.append(      np.sum(2*np.pi * b * B_oh)*dn )
  F_zodiac.append(  np.sum(2*np.pi * b * B_zodiac)*dn )
  F_stars.append(   np.sum(2*np.pi * b * B_stars)*dn )
  F_zodiac2.append( np.sum(2*np.pi * b * B_zodiac2)*dn )
  F_stars2.append(  np.sum(2*np.pi * b * B_stars2)*dn )

  # Background received powers
  P_earth.append(F_earth[-1]*A_orb*cos2_factor/cos_factor) # applying dora cos(theta)
sensitivity, which here is done properly by using cos^2(theta) in the surface
brightness integral
  P_sun.append(F_sun[-1]*A_orb)  # take worst case of staring straight at sun
  P_moon.append(F_moon[-1]*A_orb)  # take worst case of staring straight at moon
  P_moonglow.append(F_moonglow[-1]*A_orb*cos_factor)  # apply dora cos(theta)
sensitivity
  P_o2.append(F_o2[-1]*A_orb) # apply dora cos(theta) sensitivity
  P_oh.append(F_oh[-1]*A_orb*cos_factor)
  P_zodiac.append(F_zodiac[-1]*A_orb*cos_factor)
  P_stars.append(F_stars[-1]*A_orb*cos_factor)
  P_zodiac2.append(F_zodiac2[-1]*A_orb*cos_factor)
  P_stars2.append(F_stars2[-1]*A_orb*cos_factor)

  # Link fluxes and received powers
  F_link_gnd.append(P_trans_orb / (beam_angle_orb * R_orbit)**2)
  F_link_orb.append(P_trans_gnd / (beam_angle_gnd * R_orbit)**2)

  P_link_gnd.append(F_link_gnd[-1]*A_gnd)
  P_link_orb.append(F_link_orb[-1]*A_orb)

  print('')
  print('--------------------------------------------------------------------')
  print('*** BAND: {} ***'.format(name))
  print('--------------------------------------------------------------------')
  print('')
  print('++ Link flux at orbit:\t{:.4g} W/m^2'.format(F_link_orb[-1]))
  print('++ Link flux at ground:\t{:.4g} W/m^2'.format(F_link_gnd[-1]))
```

```
  print('')
  print('Flux from Earth:\t\t{:.4g} W/m^2'.format(F_earth[-1]))
  print('Flux from Sun:\t\t\t{:.4g} W/m^2'.format(F_sun[-1]))
  print('Flux from Moon:\t\t\t{:.4g} W/m^2'.format(F_moon[-1]))
  print('Flux from Moon glow:\t{:.4g} W/m^2'.format(F_moonglow[-1]))
  print('Flux from O2 lines:\t\t{:.4g} W/m^2'.format(F_o2[-1]))
  print('Flux from OH lines:\t\t{:.4g} W/m^2'.format(F_oh[-1]))
  print('Flux from Zodi.:\t\t{:.4g} W/m^2'.format(F_zodiac[-1]))
  print('Flux from stars:\t\t{:.4g} W/m^2'.format(F_stars[-1]))
  print('Flux from Zodi. #2:\t\t{:.4g} W/m^2'.format(F_zodiac2[-1]))
  print('Flux from stars #2:\t\t{:.4g} W/m^2'.format(F_stars2[-1]))
  print('')
  print('++ Link power at orbit:\t{:.4g} W \t\t= {:.4g} dBm'.format(P_link_orb[-1],
10*np.log10(P_link_orb[-1]*1e3)))
  print('++ Link power at ground:{:.4g} W \t\t= {:.4g} dBm'.format(P_link_gnd[-1],
10*np.log10(P_link_gnd[-1]*1e3)))
  print('')
  print('Power from Earth:\t\t{:.4g} W \t= {:.4g} dBm'.format(P_earth[-1],
10*np.log10(P_earth[-1]*1e3)))
  print('Power from Sun:\t\t\t{:.4g} W \t\t= {:.4g} dBm'.format(P_sun[-1],
10*np.log10(P_sun[-1]*1e3)))
  print('Power from Moon:\t\t{:.4g} W \t= {:.4g} dBm'.format(P_moon[-1],
10*np.log10(P_moon[-1]*1e3)))
  print('Power from Moon glow:\t{:.4g} W \t= {:.4g} dBm'.format(P_moonglow[-1],
10*np.log10(P_moonglow[-1]*1e3)))
  print('Power from O2 lines:\t{:.4g} W \t= {:.4g} dBm'.format(P_o2[-1],
10*np.log10(P_o2[-1]*1e3)))
  print('Power from OH lines:\t{:.4g} W \t= {:.4g} dBm'.format(P_oh[-1],
10*np.log10(P_oh[-1]*1e3)))
  print('Power from Zodi.:\t\t{:.4g} W \t= {:.4g} dBm'.format(P_zodiac[-1],
10*np.log10(P_zodiac[-1]*1e3)))
  print('Power from stars:\t\t{:.4g} W \t= {:.4g} dBm'.format(P_stars[-1],
10*np.log10(P_stars[-1]*1e3)))
  print('Power from Zodi.#2:\t\t{:.4g} W \t\t= {:.4g} dBm'.format(P_zodiac2[-1],
10*np.log10(P_zodiac2[-1]*1e3)))
  print('Power from stars #2:\t{:.4g} W \t\t= {:.4g} dBm'.format(P_stars2[-1],
10*np.log10(P_stars2[-1]*1e3)))
  print('')


plt.figure(1)
plt.plot(lambdas/dn, np.transpose(band))
plt.ylim([-0.1, 2])
plt.xlabel('Wavelengths [nm]')
plt.ylabel('Band weights')
plt.legend(band_name)
plt.title('Detector and filter bands')

plt.figure(2)
plt.semilogy(lambdas/dn, (band[2]+band[3])*F_link_gnd[0], 'k-')
plt.semilogy(lambdas/dn, B_earth*np.pi*2*cos2_factor*dn, 'k--')
plt.semilogy(lambdas/dn, B_moonglow*np.pi*2*cos2_factor*dn, 'r:')
#plt.semilogy(lambdas/dn, lambdas*B_sun*np.pi*2*cos_factor*dn)
plt.semilogy(lambdas/dn, band[0]*B_o2*np.pi*2*cos_factor*dn, 'r-')
plt.semilogy(lambdas/dn, band[1]*B_oh*np.pi*2*cos_factor*dn, 'g-')
plt.semilogy(lambdas/dn, np.ones(lambdas.shape)*B_zodiac*np.pi*2*cos_factor*dn, 'b-')
plt.semilogy(lambdas/dn, B_zodiac2*np.pi*2*cos_factor*dn, 'b:')
plt.ylim([1e-20, 1e-4])
plt.xlabel('Wavelengths [nm]')
plt.ylabel('Flux density [W/m$^2$/nm]')
plt.legend(['Link at ground', 'Earth BB', 'Reflected Moonlight', 'O$_2$ lines', 'OH
lines', 'Zodiacal light', 'Zodiacal light case #2'])
plt.title('Modeled flux densities')
```